Naval Research Laboratory
Washington, DC 20375-5320 NRL/PU/6110--97-348

MTADS TECHEVAL DEMONSTRATION

October 1996

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **OCT 1996**	2. REPORT TYPE	3. DATES COVERED **00-00-1996 to 00-00-1996**

4. TITLE AND SUBTITLE **MTADS Techeval Demonstration**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Navy Research Laboratory,4555 Overlook Ave SW,Washington,DC,20375**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**46**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

The Environmental Security Technology Certification Program (ESTCP) provided funding to the Naval Research Laboratory (NRL) for the development and demonstration of a Multi-sensor Towed Array Detection System (*MTADS*) for the detection and classification of unexploded ordnance (UXO). The *MTADS* incorporates both cesium vapor full-field magnetometers and active, pulsed-induction sensors. The sensors are mounted as linear arrays on low-signature platforms that are towed over survey sites by an all-terrain vehicle. The position-over-ground is plotted using state-of-the-art Real-Time Kinematic, On-the-Fly (RTK/OTF) resolution of integer ambiguities, a GPS technology that also provides vehicle guidance during the survey. Using mature sensor technologies, NRL has focussed on careful integration of the Data Acquisition System (DAQ) and development and integration of a sophisticated Data Analysis System (DAS). The DAS is designed to locate, identify, and categorize all military ordnance at its maximum probable self-burial depths. The DAS is efficient and simple to operate.

The performance of the *MTADS* system has been evaluated during the course of a three-phase demonstration plan. The first of these was a technical evaluation ("TECHEVAL") demonstration at the Naval Research Laboratory's Chesapeake Bay Detachment (CBD) in October 1996 to verify compliance with system requirements and performance specifications. During this demonstration, a database of sensor responses to diverse ordnance items at multiple depths and orientations was generated. The second demonstration was conducted at the Magnetic Test Range (MTR) at the Marine Corps Air Ground Combat Center (MCAGCC) in Twentynine Palms, CA in December 1996. The final demonstration was conducted in January 1997 in which the *MTADS* was evaluated at three ten-acre sites at Jefferson Proving Grounds, following the completion of JPG III commercial demonstrations.

This report summarizes the results of the TECHEVAL at CBD. Conducted over a two week period, the TECHEVAL afforded an opportunity to measure the performance of the integrated *MTADS* system against its design specifications, collect an extensive set of magnetometer and pulsed-induction signatures of inert, test ordnance items, and introduce the *MTADS* system to a variety of DOD and industry personnel.

In part one of the demonstration, the *MTADS* was evaluated against a list of performance specifications outlined in the TECHEVAL test plan. As expected, 21 of the predefined test items were satisfactorily completed. We identified three significant shortcomings for which an improvement plan was formulated. Three other, minor items were identified as not yet completed due to lack of time before the demonstration. These have been addressed subsequently.

The ordnance signature collection was also completed successfully. We collected, analyzed, and cataloged over 135 different magnetometer and pulsed-induction signatures. The collection and analysis of these signatures have been presented at two professional society meetings and in a publication submitted to the Journal of Environmental and Engineering Geophysics. To date, we have received approximately two dozen requests for these data from government, academic, and private sector investigators in the UXO field. The average location error for the magnetometer analysis was 15 cm and the depth was predicted correctly to ±20%. For the EM signatures, the location error was 11 cm but the depth estimates were not as good. We have identified a significant deviation from the spherical approximation in the measured EM signatures that causes the depth estimation errors and are investigating methods to include this effect in the DAS.

1. INTRODUCTION

1.1 Background

Unexploded ordnance (UXO) is arguably one of the most serious and prevalent environmental problems currently facing DoD facility managers. Certainly, it is among the environmental issues that will be the most expensive to mitigate and remediate. Often UXO is co-located with other environmental threats including ordnance explosive wastes (OEW), chemical wastes, and other toxic and hazardous materials. These problems occur at active sites and test ranges, at DoD sites that are currently dormant, and at many sites adjacent to military ranges that belong to the civilian sector or are under control of other government agencies. UXO becomes a problem of compelling proportions when DoD lands are classified as Formerly Used Defense Sites (FUDS) or become part of the Base Realignment and Closure (BRAC) process. Land on FUDS and BRAC sites must be evaluated, remediated as appropriate, and certified as suitable for the planned end use after disposition. Oversight and evaluation of these processes involves non-DoD agencies and the civilian community.

Current available techniques for UXO detection, site characterization, and remediation are very slow, labor intensive, and inefficient. Typical detection and characterization technologies involve handheld detectors operated by walking explosives ordnance disposal (EOD) or civilian technicians. This process is time consuming, is sometimes dangerous, and is well documented as inefficient.[1] Many ordnance items are disguised by the presence of extensive clutter and fragments from ordnance operations. Large and deep ordnance targets are often not found because either their footprints are too large to be "visualized" by the walking operator or their signatures are obscured by magnetic variations associated with geophysical anomalies. The *MTADS* technology is designed to address these issues.

The Environmental Security Technology Certification Program (ESTCP) provided funds to NRL for the development and demonstration of a multi-sensor vehicular towed array system. The *MTADS* incorporates both Cs-vapor, full-field magnetometers and active, pulsed induction sensors. These sensors are mounted in linear arrays on low-signature platforms and towed over survey sites by an all terrain vehicle. The position-over-ground is plotted using Differential Global Positioning System (DGPS) technology that also guides the survey. The largest single investment in the *MTADS* program was devoted to developing a Data Analysis System (DAS) to identify and characterize all military ordnance at its maximum probable self-burial depths, differentiate against non-ordnance clutter and be efficient and simple to operate. The *MTADS* system has been tested in three demonstrations. The first of these was effectively a technical evaluation, "TECHEVAL" demonstration at the NRL Chesapeake Bay Detachment (CBD) and is the subject of this report. The second demonstration took place at the Magnetic Test Range (MTR) at the Marine Corps Air Ground Combat Test Center (MCAGCC) in Twentynine Palms, CA in December 1996. In January 1997, the *MTADS* was demonstrated at the Jefferson Proving Grounds test site following the completion of the JPG III commercial demonstrations.

1.2 Objective of the Demonstration

The objective of this demonstration was to carry out a TECHEVAL of the complete *MTADS*. It was evaluated against the major specifications and performance requirements stated in the *MTADS* Program Management Plan.[2] Additionally, we collected magnetic and electromagnetic signature data for a range of military ordnance items at a full range of depths and orientations. These data were used to evaluate and improve the DAS performance for subsequent demonstrations. The results also constitute a data set that will be valuable for future target recognition algorithm development.

2. TECHNOLOGY DESCRIPTION

2.1 *MTADS* Description

The *MTADS* technology has been described in detail previously.[3-7] The performance of many of the *MTADS* system components, and some of the subsystems, against the requirements and procurement specifications had been tested and verified prior to this demonstration. Briefly, the system hardware includes a low-magnetic-signature vehicle that is used to tow linear arrays of magnetic and electromagnetic (EM) sensors to conduct large-area surveys to detect buried UXO. The *MTADS* Tow Vehicle, manufactured by Chenowth Racing Vehicles, is a custom-built off-road vehicle specially modified to have an extremely low magnetic signature. Most ferrous components have been removed from the body, drive train, and engine and replaced by nonferrous alloys. The vehicle is powered by a modified Volkswagen aluminum engine.

Figure 1. The *MTADS* Tow Vehicle

Details of the vehicle's construction and performance are described in the Vehicle Manuals.[8-10]

Figure 2. The *MTADS* passive sensor platform with eight magnetometers configured as a linear array

The *MTADS* magnetic sensors are full-field Cs-vapor magnetometers (a variant of the Geometrics 822 sensor, designated as the Model 822ROV). Eight sensors are deployed either as a magnetometer array or as four gradiometers measuring the vertical component of the Earth's total field. The time-dependence of the Earth's field is measured by a ninth sensor deployed at a static site during survey operations. The magnetometers were acceptance-tested at the manufacturer's facility to verify sensitivity, sensor noise, heading error, dead zones, intersensor compatibility, and performance with the multisensor interface modules.[2]

The EM sensors form an array of three pulsed induction sensors (a variant of the Geonics EM-61 instrument). These sensors, deployed in an overlapping horizontal array, transmit a tailored electromagnetic pulse into the Earth. Metallic objects efficiently absorb the energy, setting up eddy currents that reradiate electromagnetic energy. This signal is time-sampled by six detection coils colocated with the three transmission coils. The commercial EM-61 pulsed induction sensors were redesigned based upon laboratory and field studies, manufactured to our requirements, delivered, and tested at NRL. They were subsequently returned to the manufacturer for final adjustments before integration into the array and onto the platform. TECHEVAL was, in part, designed to test their performance as an array against detection requirements.

The sensor positions on the surface of the Earth (latitude, longitude, and height above ellipsoid) are determined using DGPS navigation, employing Real Time Kinetic (RTK) technology which provides a real-time position update (at 1 Hz) with an accuracy of about 5 cm. Satellite-derived time data is used to time-stamp both position and sensor data information for later correlation. In addition, an electronic compass, attitude sensors (pitch, roll and yaw), and tick wheel sensors provide navigation backup and dead-reckoning capability. All navigation and sensor data are provided through electronic interfaces to the DAQ computer (DAQ) in the Tow Vehicle. The guidance computer serves as a survey set-up and guidance tool. What remained for testing at TECHEVAL was the performance of the navigation system following integration with the DAQ system developed for the Tow Vehicle.

Perimeter surveys or point landmarks are used to define the survey bounds. The Guidance Computer develops a survey track grid that is presented to the vehicle operator *via* a touchscreen display located beside the steering wheel. The survey course-over-ground is plotted in near-real time on the display, as are presentations of the course heading error and distance-off-track information. This allows the operator to respond to both visual cues on the ground and to the survey guidance display. Following a survey, the operator can return to survey missed areas before leaving the survey area.

Survey data is downloaded onto tape or hard wire connection to a notebook computer for transfer to the DAS computer. The DAS software was developed specifically for this program as a standalone suite of programs written using IDL development tools and

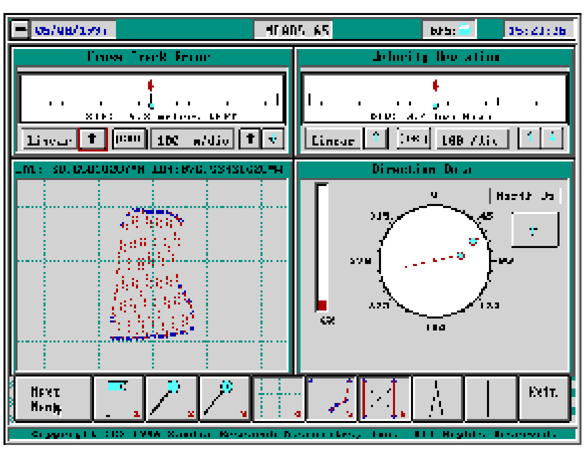

Figure 5. Screen image of the *MTADS* guidance system showing survey tracks and guidance compass

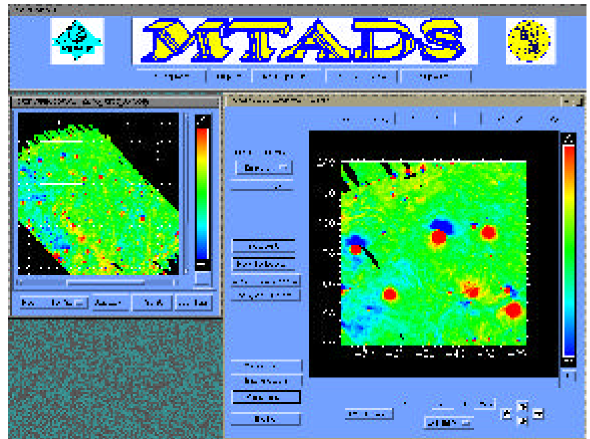

Figure 3. The *MTADS* active sensor platform with three EM-61 sensors configured as an array

Figure 6. Analysis window of the *MTADS* Data Analysis System

graphics user interfaces (GUIs) working in a UNIX-based workstation environment. The DAS is written at multiple levels for both sophisticated and novice users. Menu-driven widgets can lead a fairly novice user through a complete data analysis using background default analysis settings. A range of expert options are also available to allow navigation data cleanup, sensor nulling and leveling, noise filtering, and other electronic data preprocessing options.

The DAS uses resident physics-based algorithms to carry out survey target analyses interactively using magnetometry, gradiometry, and EM data. Extensive training data sets (using inert ordnance) were taken as

Figure 4. The GPS receiver associated with the navigation reference station

part of this demonstration and used to refine the algorithms to improve target analysis. In addition to position, depth, and size solutions, magnetic analyses provide target orientation and effective caliber information and, using a "goodness of fit" analysis, provide guidance in distinguishing ordnance from non-ordnance targets. The performance of the Data Analysis System components have been tested against simulated data and against data taken with earlier versions of *MTADS*. TECHEVAL was used to evaluate the DAS performance using data taken by the fully integrated *MTADS* system. The data sets taken in Demonstration 1 were used not only to evaluate the performance of the DAS, but were used to refine its performance.

2.2 Advantages and Limitations of the Technology

The best ordnance detection performances at JPG I and JPG II were based upon the use of Cs vapor full-field magnetometers or Geonics EM-61 sensors.[11-13] These same commercial magnetometers and EM sensors have also turned in <u>much less impressive</u> results in the hands of other demonstrators at JPG. How they are deployed in taking the data, and probably more importantly, how the data are processed and analyzed to recognize and characterize targets, are clearly critical to achieving optimal results.

The NRL sensor specifications and performance results of the Geometrics 822ROV sensors are described in the sensor performance test reports delivered with the sensors. The Geonics EM-61 sensors have been extensively modified. These modifications include changing the time position and time width of the sampling window monitoring the return signal. The power of the transmitted pulse has been increased, as has the pulse repetition rate. The amplifier gain of the detector has been increased and the time constant applied to this signal has been significantly reduced. The overall detection signal has been increased by a factor of 3 to 6, depending upon the composition, depth, and size of the target.

The *MTADS* DAS software is truly third generation. We have, over a period of 10 years, completed two earlier DAS developments with two other contractors. In this program, we build upon the successes of the earlier efforts and address the shortcomings that we recognized in earlier DAS performance in more than a dozen ordnance surveys at prepared sites and in a variety of live ordnance settings that were followed by documented remediations.

We do not believe that there are weaknesses in the *MTADS* system compared with other commercial or competing developmental technologies. We believe that the sensors, the field hardware, and the DAS software are truly state-of-the-art for this type of application. There are, however, some limitations of the *MTADS* system imposed by the development schedule, by limitations imposed on the budget by unintended costs, and by the relatively virgin state of the system when it will be carried to the field.

Other than the lack of rigorous real-world shakedown experience prior to Demonstrations 2 and 3, we recognize three significant shortcomings of the current system. A backup navigation system is needed for *MTADS* to augment DGPS. DGPS is not effective where sky visibility is limited. This is a severe limitation in urban settings or in situations with mountains or significant tree cover. Our dead-reckoning capability is intended to provide fill-in for loss of satellite navigation for up to 20 seconds (with degraded accuracy). Ultimately, DGPS navigation <u>must be</u> augmented by a backup system (microwave, acoustic, laser, or inertial navigation systems), or surveyors must be prepared to conduct extensive line or grid surveys to augment *MTADS* vehicular survey data.

Budgetary constraints did not permit development of a credible man-portable adjunct survey capability. The component technologies <u>are</u> available and could be integrated into such a system. However, doing so is beyond the scope of the current effort. A well-designed (and relatively inexpensive) man-portable *MTADS* has significant transition capability. The main transition potential of *MTADS* is to companies who wish to provide services. It is too expensive for an extensive commercial market. The same is not true of a simpler standalone man-portable system.

Finally, *MTADS* has not developed a true sensor data fusion capability. We take independent magnetometry, gradiometry, and EM data sets. The analysis results are overlaid with each other and we use the strengths of each system to recognize ordnance targets and to eliminate false targets. However, a significantly greater potential exists. With the extensive training data sets taken at CBD and at Twentynine Palms, sufficient information will exist to create an expert system that would potentially be much more powerful than the correlative approach that we will use in our demonstrations.

3. SITE/FACILITY DESCRIPTION

Figure 7. The CBD test pit used for shallow tests of smaller ordnance items

Figure 8. Fiberglass liner of the test well being lowered into place at CBD

3.1 Site/Facility History

The demonstration was conducted at the Naval Research Laboratory, Chesapeake Bay Division Facility in Chesapeake Beach, MD. The test site consists of a few hundred square feet adjacent to what was the former ball field on the West Field site. Two test facilities have been constructed on this small area. The first is a pit designed to accommodate inert ordnance items to a depth of one meter below the surface. Ordnance items are precisely oriented and placed on nonmetal trays within the pit. The pit is covered to allow the vehicle and sensor platforms to be driven over the site.

The larger test well was bored to a diameter of 1.4 meters and a depth of 7 m using a drilling rig. The well was lined with a nonmetallic (fiberglass) casing 48 inches in diameter. Wooden 2 in. X 6 in. stringers placed below ground level allow for suspending ordnance items within the well. The surface of the well is covered with wood planking flush with grade.

3.2 Site/Facility Characteristics

The test pit and well are described in Section 3.1. The geology at CBD in the region of the test area consists of a surface layer of loam/clay 1 to 2 ft thick. This is underlain by mixed clay and sand and then sand to a depth of >20 ft. The geophysical soil parameters are irrelevant to the operation of the *MTADS*, as it sees no difference in the return signal from the native soils compared with the air cavities in the pit and well.

4. DEMONSTRATION APPROACH

4.1 Performance Objectives

The objectives of this demonstration were three-fold. First, we completed a TECHEVAL of the *MTADS* system against design requirements and performance specifications. Second, we used the *MTADS* to build a test and training data set for the full range of specified ordnance (that fall within the depth design detection limits) for all sensor arrays. This second objective provided an evaluation of the *MTADS* ordnance detection sensitivity limits, the ability to identify and characterize ordnance, and an evaluation of many of the performance characteristics that will determine the support requirements for later demonstrations. The results form an initial basis for evaluating performance costs for *MTADS* in field survey applications. The third objective was to conduct an Open House Demonstration at the NRL CBD, to demonstrate the performance of the *MTADS* system. The Open House allowed us to demonstrate the *MTADS* performance to sponsor representatives and other interested parties and to complete the technical requirements associated with this Demonstration.

Table 1 lists the system component performance criteria that were evaluated during the TECHEVAL demonstration process. *MTADS* performance tests against some of the system specifications, such as those involving survey endurance, mass data storage

capabilities, were evaluated in the later demonstrations. vehicle

The test and training data sets taken during Demonstration 1 were displayed and described at the Open House. The data were used to refine the fitting algorithms for the magnetic and EM sensors prior to the second demonstration at Twentynine Palms. We also anticipate that the training data set will have significant appeal and value associated with the *MTADS* transition to the commercial sector. Additionally, the data could form the basis for development of data analysis systems by other organizations using these or other similar sensors. The development of multisensor data fusion algorithms for magnetic and EM sensors could also take advantage of these data sets. We have described the data themselves[14] and the analysis methods employed[15] at professional society meetings and have submitted a manuscript describing the data and analysis to the *Journal of Environmental and Engineering Geophysics*.[16] These presentations have resulted in approximately two dozen requests for the data from other governmental groups in addition to academic institutions and private sector firms.

4.2 Physical Setup and Operation

4.2.1 Demonstration Setup for the DAQ, Navigation, and DAS Systems

During the first week of Demonstration 1, the *MTADS* performance relative to specifications addressed in the Program Plan and in Table 1 of this document were tested. This included components of the DAQ system and the entire navigation system following integration into the *MTADS* Tow Vehicle.

The DAQ System A site of ~10,000 square feet was chosen at CBD to create a demonstration survey. The survey setup form was used to set up the sensors, initiate correct operation of the navigation system and reference sensors and initiate all other operations in preparation for beginning a new survey. Both static and dynamic (driving the perimeter) landmark files were created. The guidance system automatically sets up a survey grid based upon the landmark data file. A survey was conducted using this prepared grid. The touchscreen display was used to demonstrate survey progress at an appropriate scale, correctly plotting course-over-ground while creating a missed area map. The touchscreen was used to display navigation quality information and color-coded RTK, DGPS, or DR data. Driving aids, including compass heading and off track information, were evaluated for utility to the

operator. The missed area map, generated by the DAQ, was used to direct the surveyor to accessible missed areas to complete 100% coverage of the site. All sensor, reference, landmark, and navigation files were correctly closed and saved. These files were downloaded onto floppy disk (in a zipped format), to the output tape drive, and using a portable notebook computer, downloaded via a parallel cable for transport to the DAS.

The ability of the DAQ to support 8 hours of survey data with 4 hours of continuous operation before file closeouts was demonstrated at Twentynine Palms where much larger survey data sets were taken. The target landmarking capability of the DAQ and the Tow Vehicle was likewise tested at Twentynine Palms as a planned part of Demonstration 2.

Table 1. TECHEVAL Performance Criteria for *MTADS* Components

Subsystem	**Requirement**	**Evaluation Criteria**
DAQ	Sensor Data Streams	Correctly formats and time stamps all data
	Survey Land Marking	Incorporates both static and dynamic landmarks
	Survey Planning	Sets up survey grid based upon landmark data
	Survey Guidance	Displays real-time survey progress map Displays heading and off-track information Correctly displays degrading from RTK to DGPS to DR Correctly displays missed areas and guides the survey operator
	Target Land Marking	Sets up scheme and directs target reacquisition and marking, allowing waypointing 5 acres/day with 20 targets/acre
	Survey	Accommodates 8 hours of survey data Correctly prepares output files for download
Navigation	Operational Position Accuracy	($x,y < 0.03$ m, $z < 0.05$ m)
	Dead-Reckoning Sensors	Incorporate data into Navfill, maintaining position accuracy during RTK holidays of up to 20 seconds, using inertial navigation and compass aids
	Reference Station	Supports Mobile Unit using RF Repeaters
Field Hardware	Tow Vehicle	Ability to support vehicle, DAQ, and all sensors for 8 hours on internal batteries without recharge and will accommodate 4 hours of continuous data collection

Table 1. TECHEVAL Performance Criteria for *MTADS* Components

Subsystem	**Requirement**	**Evaluation Criteria**
	Magnetometers	Demonstrate performance against procurement specs when deployed as magnetometer and gradiometer arrays
	EM Sensors	Successfully demonstrate performance against procurement specs when deployed as an overlapping array
DAS	Preprocessing	Correctly merges all landmark, sensor, navigation, and reference files Generates all necessary navigation and noise spectra plots Incorporates commercial software to postprocess data during loss of radio link while surveying
		Successfully produces all necessary navigation editing and corrections Successfully performs all expert sensor data correction modules
	Processing	Analyzes all targets for location, depth, and size within specs for all sensor arrays Demonstrates ability to locate targets in a large gradient offset using the gradiometer system Demonstrates the ability to correctly analyze large targets in the presence of surface clutter Provides specified output files for DAQ to landmark targets Provides required output graphics and tables correctly formatted and font- and color-corrected Demonstrates an analysis system to successfully correlate multisensor data sets Demonstrates ability to create topographic maps correlated with magnetic anomaly mapping Demonstrate graphic output capability compatible with GIS format requirements

The Navigation System GP Surveyor software was used in preparation for the survey described in the previous paragraph to evaluate satellite availability and graphically display their positions and orbits during the planned survey. The survey setup sheet was used to set up and initialize the base station, RF repeater, and the roving navigation systems.

The correct synchronization of the satellite timing signals with the sensor data have been demonstrated using two experimental setups. In the first experiment, a coil is wrapped around a magnetometer. The coil is energized, following a fixed time delay, by the 10 ns satellite timing flag. The induced signal in the magnetometer file is compared with the clock signal

recorded in the navigation file. The match up in timekeeping has been demonstrated to be better than 1 msec, corresponding to <3mm position uncertainty in the magnetometer and EM data files. In a second experiment, a loop of wire is laid across the sensor track and activated by passing a DC current through the wire. A survey is taken repeatedly crossing the signal wire from opposite directions. The induced signal positions from each sensor are displayed in an X-Y plot. The matchup of signal peaks falls within the required position accuracy for the system. The latter measurement displays the combined uncertainties from both the timing synchronization with the sensor data files and the computational corrections for the sensor positions relative to the DGPS antenna including heading uncertainties and position interpolations between satellite timing updates.

The system navigation accuracy was also evaluated by two other types of measurements taken during TECHEVAL. There are several known first-order sites in the West Field area that were surveyed as part of our navigation system tests.[17] Each of these is marked by a rebar driven into the ground and capped by a survey plate. Several of these are accessible and were dynamically surveyed using both the magnetometer and EM Tow Platforms. The analyzed "target" positions of the markers were compared with their known survey coordinates.

Each data set taken with the magnetometer or EM arrays using the test pit or the test well was analyzed for target positions that were compared with the precisely known positions of the ordnance in the test fixtures. These measurements provided several hundred additional evaluations of target location accuracy. These measurements provide a statistical database to evaluate the overall location accuracy of the full-up *MTADS* system and independent evaluations of the two types of sensor systems for different types, sizes, and depths of targets.

DAS Preprocessing Landmark, sensor, navigation, and reference files from the 10,000 square foot survey described above were preprocessed using the DAS system demonstrating correct and compatible formatting for all the field data files. The DAS Navfill processing software made course-over-ground plots, plots of computed navigational heading, and plots displaying RTK, DGPS, and Dead-Reckoning navigation. All available navigation processing tools were exercised to demonstrate the full capability of the

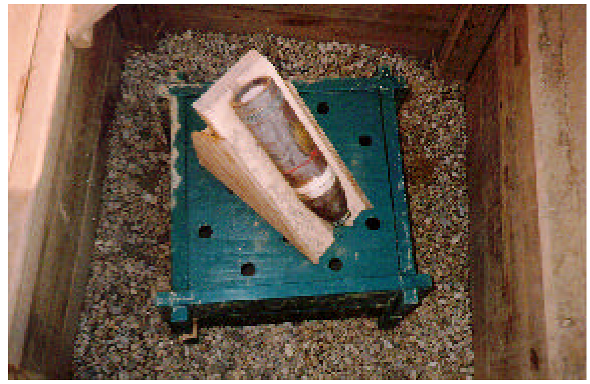

Figure 9. Test ordnance placed for signature acquisition in the *MTADS* test pit

Navfill preprocessing routines maintaining specified position accuracy during RTK holidays.

DAS Processing Using the survey data described in the previous and following sections, the DAS generated sensor data quality plots to demonstrate the noise spectra associated with the data. These plots were used to demonstrate sensor noise filtering and other components of the expert level of the DAS. The ability to compensate for large magnetic field gradients in a survey area was demonstrated. Target analyses (described in detail in the following section) were carried out to demonstrate analysis accuracies specified in the requirements. The DAS provided the required output graphics and tables correctly formatted and font, pitch, and color corrected. Output graphics and tables were generated in local grids in meters and in latitude/longitude.

4.2.2 *MTADS* Ordnance Signature Acquisition Test Plan

The *MTADS* program has developed a test facility for ordnance signature acquisition at the NRL/CBD site, as described in Section 3.1. The test well and test pits are located in an area that is magnetically moderately contaminated. The test site and adjacent areas have good sky view for GPS. Located nearby is a precisely known position (CBD 6110-3) for GPS base station use.[17] These characteristics make the test facility appropriate for the acquisition of ordnance signatures using all the *MTADS* sensor suites.

The sensors employed by *MTADS* are Cs-vapor magnetometers arranged as a linear array of 8 sensors for total field measurements (with 0.25 meter horizontal separation) or as an array of 4 over 4 for vertical gradient measurements. Gradiometer horizontal separations can be either 0.25 or 0.5 meters. An array of specially modified Geonics EM-61 pulsed

induction sensors is deployed on a specially manufactured fiberglass and composite sensor platform trailer. The test plan addresses the acquisition of ordnance signatures, both alone and in the presence of fragment clutter, using these sensors. A goal of this demonstration was the acquisition of a complete, controlled set of data for model development, training, and sensor fusion.

Test Matrix A description of the test matrix follows. Table 2, lists the ordnance items proposed for testing and the depths and orientations at which signatures were to be collected using the magnetometer array. The depths range from the maximum probable depth at which an individual item is likely to be found and upward in convenient steps. Also listed in Table 2 are the planned E-W survey widths and the magnetometer spacings. All surveys were conducted in a S-N direction because of restrictions at the site. The standard magnetometer horizontal spacing is 0.25 m (resulting in a total array width of 1.75 m). Combined with a lane spacing of 2 m, this results in E-W survey widths of 1.75, 3.75. Figure 10 illustrates a 5.75 m wide survey.

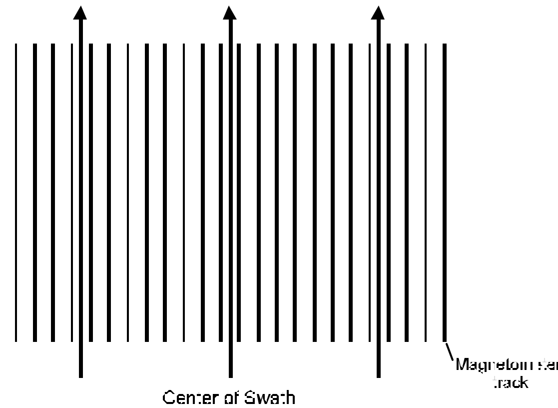

Figure 10. Example of a 5.75 m wide survey consisting of three passes of the *MTADS* Tow Platform. The long vertical lines (with arrowheads) denote the tow vehicle paths and the other vertical lines trace the individual sensor tracks.

Because of the number of surveys required to complete the matrix in Table 2 was very large, we divided the study into two data sets. Table 3 lists the first priority data taken during the demonstration using the magnetometer array. The remainder of the data to complete the measurements in Table 2 were to be completed as time allowed during the program.

Table 2. Proposed Magnetometer Test Matrix for Ordnance Signature Acquisition.

Ordnance Item	Depths (m)	E-W Survey Width (m)	Mag Spacing (cm)	Azimuth Steps	Inclination Steps
20 mm projectile	surface	1.875	12.5	N/A	N/A
30 mm projectile	surface	1.875	12.5	N/A	N/A
M42 grenade	0.15 & surface	1.875	12.5	N/A	N/A
M46 submunition	0.15 & surface	1.875	12.5	N/A	N/A
60 mm mortar	1¼, 1, ¾, ½	3.75	25	22.5°	22.5°
2.75" rocket	1½, 1¼, 1, ¾	3.75	25	22.5°	22.5°
81 mm mortar	2, 1½, 1¼, 1, ¾	5.75	25	22.5°	22.5°
105 mm projectile	3, 2½, 2, 1½, 1	7.75	25	22.5°	22.5°
4.2 in. mortar	3, 2½, 2, 1½, 1	7.75	25	22.5°	22.5°
5 in. rocket	3, 2½, 2, 1½, 1	7.75	25	22.5°	22.5°
155 mm projectile	3½, 3, 2½, 2, 1½	9.75	25	22.5°	22.5°
Mk 82 500 lb bomb	6, 4½, 3,1½	13.75	25	22.5°	22.5°
Mk 83 1000 lb bomb	6, 4½, 3, 1½	13.75	25	22.5°	22.5°

both position and sensor data information for later correlation. In addition, an electronic compass, attitude sensors (pitch, roll and yaw), and tick wheel sensors provide navigation back-up and dead-reckoning capability. All navigation and sensor data are provided through electronic interfaces to the Data Acquisition Computer (DAQ) in the Tow Vehicle. The Guidance computer serves as a survey set-up and guidance tool. What remained for testing at TECHEVAL was the performance of the navigation system following integration with the DAQ system developed for the Tow Vehicle.

Perimeter surveys or point landmarks are used to define the survey bounds. The Guidance Computer develops a survey track grid that is presented to the vehicle operator *via* a touch screen display located beside the steering wheel. The survey course-over-ground is plotted in near-real time on the display, as are presentations of the course heading error and distance-off-track information. This allows the operator to respond to both visual cues on the ground and to the survey guidance display. Following a survey, the operator can return to survey missed areas before leaving the survey area.

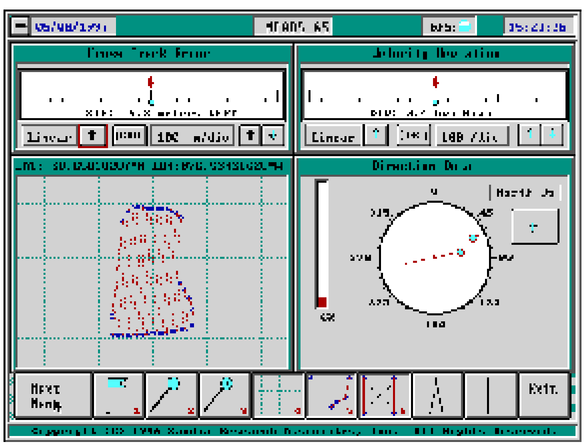

Figure 5. Screen image of the *MTADS* guidance system showing survey tracks and guidance compass.

Survey data is down-loaded onto tape or hard wire connection to a notebook computer for transfer to the DAS computer. The DAS software was developed specifically for this program as a stand alone suite of programs written using IDL development tools and graphics user interfaces (GUI's) working in a UNIX-based workstation environment. The DAS is written at multiple levels for both sophisticated and novice users. Menu-driven widgets can lead a fairly novice user through a complete data analysis using background default analysis settings. A range of expert options are

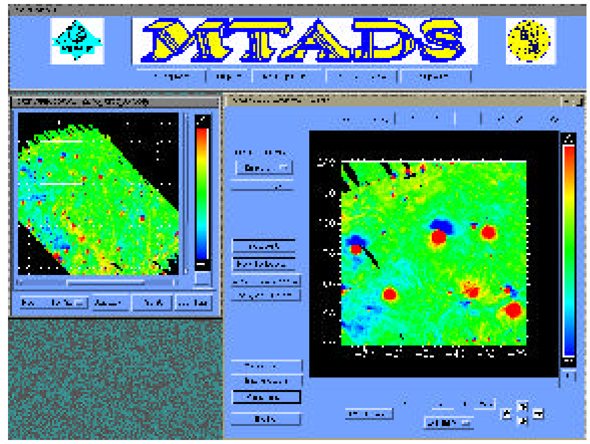

Figure 6. Fit window of the *MTADS* Data Analysis System.

also available to allow navigation data cleanup, sensor nulling and leveling, noise filtering, and other electronic data preprocessing options.

The DAS uses resident physics-based algorithms to carry out survey target analyses interactively using magnetometry, gradiometry, and EM data. Extensive training data sets (using inert ordnance) were taken as part of this demonstration and used to refine the algorithms to improve target analysis. In addition to position, depth, and size solutions, magnetic analyses provide target orientation and effective caliber information and, using a "goodness of fit" analysis, provide guidance in distinguishing ordnance from non-ordnance targets. The performance of the Data Analysis System components have been tested against simulated data and against data taken with earlier versions of *MTADS*. TECHEVAL was used to evaluate the DAS performance using data taken by the fully-integrated *MTADS* system. The data sets taken in Demonstration 1 were used not only to evaluate the performance of the DAS, but were used to refine its performance.

2.2 Advantages and Limitations of the Technology

The best ordnance detection performances at both JPG I and JPG II were based upon the use of Cs vapor full-field magnetometers or Geonics EM-61 sensors.[11-13] These same commercial magnetometers and EM sensors have also turned in much less impressive results in the hands of other demonstrators at JPG. How they are deployed in taking the data, and probably more importantly, how the data are processed and analyzed to recognize and characterize targets, are clearly critical to achieving optimal results.

The NRL sensor specifications and performance results of the Geometrics 822ROV sensors are described in the sensor performance test reports delivered with the sensors. The Geonics EM-61 sensors have been extensively modified. These modifications include changing the time position and time width of the sampling window monitoring the return signal. The power of the transmitted pulse has been increased, as has the pulse repetition rate. The amplifier gain of the detector has been increased and the time constant applied to the this signal has been significantly reduced. The overall detection signal has been increased by a factor of 3 - 6, depending upon the composition, depth, and size of the target.

The *MTADS* DAS software is truly third generation. We have, over a period of 10 years, completed two earlier DAS developments with two other contractors. In this program we build upon the successes of the earlier efforts and address the shortcomings that we recognized in earlier DAS performance in more than a dozen ordnance surveys at prepared sites and in a variety of live ordnance settings that were followed by documented remediations.

We do not believe that there are weaknesses in the *MTADS* system compared with other commercial or competing developmental technologies. We believe that the sensors, the field hardware, and the DAS software are truly state-of-the-art for this type of application. There are, however, some limitations of the *MTADS* system imposed by the development schedule, limitations imposed on the budget by unintended costs, and by the relative virgin state of the system when it will be carried to the field.

Other than the lack of rigorous real-world shakedown experience prior to Demonstrations 2 and 3, we recognize three significant shortcomings of the current system. A backup navigation system is needed for *MTADS* to augment DGPS. DGPS is not effective where sky visibility is limited. This is a severe limitation in urban settings or in situations with mountains or significant tree cover. Our dead-reckoning capability is intended to provide fill-in for loss of satellite navigation for up to 20 seconds (with degraded accuracy). Ultimately, DGPS navigation <u>must be</u> augmented by a backup system (microwave, acoustic, laser, or inertial navigation systems), or surveyors must be prepared to conduct extensive line or grid surveys to augment *MTADS* vehicular survey data.

Budgetary constraints did not permit development of a credible man-portable adjunct survey capability. The component technologies <u>are</u> available and could be integrated into such a system. However, it is beyond the scope of the current effort. A well-designed (and relatively inexpensive) man-portable *MTADS* has significant transition capability. The main transition potential of *MTADS* is to companies who wish to provide services. It is too expensive for an extensive commercial market. The same is not true of a simpler stand alone man-portable system.

Finally, *MTADS* <u>has not developed</u> a true sensor data fusion capability. We take independent magnetometry, gradiometry, and EM data sets. The results are overlaid with each other and we use the strengths of each system to recognize ordnance targets and to eliminate false targets. However, a significantly greater potential exists. With the extensive training data sets taken at CBD and at Twentynine Palms, sufficient information will exist to create an expert system that would potentially be much more powerful than the correlative approach that we will use in our demonstrations.

3. SITE/FACILITY DESCRIPTION

3.1 Site/Facility History

The demonstration was conducted at the Naval Research Laboratory, Chesapeake Bay Division Facility, in Chesapeake Beach, MD. The test site consists of a few hundred square feet adjacent to what was the former ball field on the West Field site. Two test facilities have been constructed on this small area. The first is a pit designed to accommodate inert ordnance items to a depth of one meter below the surface. Ordnance items are precisely oriented and placed on nonmetal trays within the pit. The pit is covered to allow the vehicle and sensor platforms to be driven over the site.

The larger test well was bored to a diameter of 1.4 meters and a depth of 7 meters using a drilling rig. The well was lined with a nonmetallic (fiberglass) casing 48 inches in diameter. Wooden 2 in. x 6 in. stringers placed below ground level allow for suspending ordnance items within the well. The surface of the well is covered with wood planking flush with grade.

Figure 7. The CBD test pit used for shallow tests of smaller ordnance items.

3.2 Site/Facility Characteristics

The test pit and well are described in Section 3.1. The geology at CBD in the region of the test area consists of a surface layer of loam/clay 1 to 2 feet thick. This is underlain by mixed clay and sand and then sand to a depth of >20 feet. The geophysical soil parameters are irrelevant to the operation of the *MTADS*, as it sees no difference in the return signal from the native soils compared with the air cavities in the pit and well.

4. DEMONSTRATION APPROACH

4.1 Performance Objectives

The objectives of this demonstration were three-fold. First, we completed a TECHEVAL of the *MTADS* system against design requirements and performance specifications. Second, we used the *MTADS* to build a test and training data set for the full range of specified ordnance (that fall within the depth design detection limits) for all sensor arrays. This second objective provided an evaluation of the *MTADS* ordnance detection sensitivity limits, the ability to identify and characterize ordnance, and an evaluation of many of the performance characteristics that will determine the support requirements for later demonstrations. The results form an initial basis for evaluating performance costs for *MTADS* in field survey applications. The third objective was to conduct an Open House Demonstration at the Naval Research Laboratory, Chesapeake Bay Detachment, to demonstrate the performance of the *MTADS* system. The Open House allowed us to demonstrate the *MTADS* performance to sponsor representatives and other interested parties

Figure 8. Fiberglass liner of the test well being lowered into place at CBD.

and to complete the technical requirements associated with Demonstration Number 1.

Table 1 lists the system component performance criteria that were evaluated during the TECHEVAL demonstration process. *MTADS* performance tests against some of the system specifications -- such as those involving survey endurance, mass data storage capabilities, *etc.* -- were evaluated in the later demonstrations.

The test and training data sets taken during Demonstration 1 were displayed and described at the Open House. The data were used to refine the fitting algorithms for the magnetic and EM sensors prior to the second Demonstration at Twentynine Palms. We also anticipate that the training data set will have significant appeal and value associated with the *MTADS* transition to the commercial sector. Alternatively, the data could form the basis for development of data analysis systems by other organizations using these or other similar sensors. The development of multisensor data fusion algorithms for magnetic and EM sensors could also take advantage of these data sets. We have described the data themselves[14] and the analysis methods employed[15] at professional society meetings and have submitted a manuscript describing the data and analysis to the Journal of Environmental & Engineering Geophysics.[16] These presentations have resulted in approximately two dozen requests for the data from government, academic, and private sector firms.

4.2 Physical Setup and Operation

4.2.1 Demonstration Set-up for the DAQ, Navigation

and DAS Systems

During the first week of Demonstration 1, the *MTADS* performance relative to specifications addressed in the Program Plan and in Table 1 of this document were tested. This included components of the DAQ system and the entire Navigation system following integration into the *MTADS* Tow Vehicle.

The DAQ System A site of ~10,000 square feet was chosen at CBD to create a demonstration survey. The survey setup form was used to set up the sensors, initiate correct operation of the Navigation system and Reference Sensors and initiate all other operations in preparation for beginning a new survey. Both static and dynamic (driving the perimeter) landmark files were created. The Guidance System automatically set up a survey grid based upon the landmark data file. A survey was conducted using this prepared grid. The touch screen display was used to demonstrate survey progress at an appropriate scale, correctly plotting course-over-ground while creating a missed area map. The touch screen was used to display navigation quality information and color-coded RTK, DGPS or DR data. Driving aids, including compass heading and off track information, were evaluated for utility to the vehicle operator. The missed area map, generated by the DAQ, was used to direct the surveyor to accessible missed areas to complete 100% coverage of the site. All sensor, reference, landmark, and navigation files were correctly closed and saved. These files were downloaded onto floppy disk (in a zipped format), to the output tape drive, and using a portable notebook computer, downloaded *via* a parallel cable for transport to the DAS.

The ability of the DAQ to support 8 hours of survey data with 4 hours of continuous operation before file closeouts was demonstrated at Twentynine Palms where much larger survey data sets were taken. The target landmarking capability of the DAQ and the Tow Vehicle was likewise tested at Twentynine Palms as a planned part of Demonstration 2.

Table 1. TECHEVAL Performance Criteria for *MTADS* Components

Subsystem	Requirement	Evaluation Criteria
DAQ	Sensor Data Streams	Correctly formats and time stamps all data
	Survey Land Marking	Incorporates both static and dynamic landmarks
	Survey Planning	Sets up survey grid based upon landmark data
	Survey Guidance	Displays real-time survey progress map. Displays heading and off-track information. Correctly displays degrading from RTK to DGPS to DR. Correctly displays missed areas and guides the survey operator.
	Target Land Marking	Sets up scheme and directs target reacquisition and marking, allowing waypointing 5 acres/day with 20 targets/acre
	Survey	Accommodates 8 hours of survey data Correctly prepares output files for download
Navigation	Operational Position Accuracy	(x,y < 0.03 m, z < 0.05 m)

	Dead-Reckoning Sensors	Incorporate data into N RTK holidays of up to compass aids
	Reference Station	Supports Mobile Unit u
Field Hardware	Tow Vehicle	Ability to support vehi internal batteries withou continuous data collecti
	Magnetometers	Demonstrate performan deployed as magnetome
	EM Sensors	Successfully demonstra when deployed as an o
DAS	Preprocessing	Correctly merges all lan files. Generates all necessary Incorporates commerci of radio link while surv

Table 1. TECHEVAL Performance Criteria for *MTADS* Components

Subsystem	**Requirement**	**Evaluation Criteria**
		Successfully produces all necessary navigation editing and corrections. Successfully performs all expert sensor data correction modules.
	Processing	Analyzes all targets for location, depth and size within specs for all sensor arrays. Demonstrates ability to locate targets in a large gradient offset using the gradiometer system. Demonstrates the ability to correctly analyze large targets in the presence of surface clutter. Provides specified output files for DAQ to landmark targets. Provides required output graphics and tables correctly formatted and font and color corrected. Demonstrates an analysis system to successfully correlate multisensor data sets. Demonstrates ability to create topographic maps correlated with magnetic anomaly mapping. Demonstrate graphic output capability compatible with GIS format requirements.

The Navigation System GP Surveyor software was used in preparation for the survey described in the previous paragraph to evaluate satellite availability and graphically display their positions and orbits during the planned survey. The survey set up sheet was used to set up and initialize the base station, RF repeater, and the roving navigation systems.

The correct synchronization of the satellite timing signals with the sensor data have been demonstrated using two experimental setups. In the first experiment a coil is wrapped around a magnetometer. The coil is energized following a fixed time delay, by the 10 nsec satellite timing flag. The induced signal in the magnetometer file is compared with the clock signal recorded in the navigation file. The match up in timekeeping has been demonstrated to be better than 1 msec, corresponding to <3mm position uncertainty in the magnetometer and EM data files. In a second experiment, a loop of wire is laid across the sensor track and activated by passing a DC current through the wire. A survey is taken repeatedly crossing the signal wire from opposite directions. The induced signal positions from each sensor are displayed in an X-Y plot. The match up of signal peaks falls within the required position accuracy for the system. The latter measurement displays the combined uncertainties from both the timing synchronization with the sensor data files and the computational corrections for the sensor positions relative to the DGPS antenna including heading uncertainties and position interpolations between satellite timing updates.

The system navigation accuracy was also evaluated by two other types of measurements taken during TECHEVAL. There are several known first-order sites in the West Field area that were surveyed as part of our navigation system tests.[17] Each of these is marked by a rebar driven into the ground and capped by a survey plate. Several of these are accessible and were dynamically surveyed using both the magnetometer and EM Tow Platforms. The analyzed "target" positions of the markers were compared with their known survey coordinates.

Each data set taken with the magnetometer or EM arrays using the test pit or the test well was analyzed for target positions that were compared with the precisely known positions of the ordnance in the test fixtures. These measurements provided several hundred additional evaluations of target location accuracy. These measurements provide a statistical data base to evaluate the overall location accuracy of the full-up *MTADS* system and independent evaluations of the two types of sensor systems for different types, sizes and depths of targets.

DAS Preprocessing Landmark, sensor, navigation, and reference files from the 10,000 square foot survey described above were preprocessed using the DAS system demonstrating correct and compatible formatting for all the field data files. The DAS navfill processing software made course over ground plots, plots of computed navigational heading, and plots displaying RTK, DGPS and Dead Reckoning navigation. All available navigation processing tools were exercised to demonstrate the full capability of the navfill preprocessing routines maintaining specified position accuracy during RTK holidays.

DAS Processing Using the survey data described above and in the following section, the DAS generated sensor data quality plots to demonstrate the noise spectra associated with the data. These plots were used to demonstrate sensor noise filtering and other components of the expert level of the DAS. The ability to compensate for large magnetic field gradients in a survey area was demonstrated. Target analyses (described in detail in the following section) was carried out to demonstrate analysis accuracies specified in the requirements. The DAS provided the required output graphics and tables correctly formatted and font, pitch and color corrected. Output graphics and tables were generated in local grids in meters and in latitude/longitude.

4.2.2 *MTADS* Ordnance Signature Acquisition Test Plan

The *MTADS* program has developed a test facility for ordnance signature acquisition at the NRL/CBD site, as described in Section 3.1. The test well and test pits are located in an area that is magnetically moderately contaminated. The test site and adjacent areas have good sky view for GPS. Located nearby is a precisely known position (CBD 6110-3) for GPS base station use.[17] These characteristics make the test facility appropriate for the acquisition of ordnance signatures using all the *MTADS* sensors suites.

The sensors employed by *MTADS* are Cs-vapor magnetometers arranged as a linear array of 8 sensors for total field measurements (with 0.25 meter horizontal separation) or as an array of 4 over 4 for vertical gradient measurements. Gradiometer horizontal separations can be either 0.25 or 0.5 meters. An array of specially modified Geonics EM-61 pulsed induction sensors is deployed on a specially manufactured fiberglass and composite sensor platform trailer. The test plan addresses the acquisition of ordnance signatures, both alone and in the presence of fragment clutter, using these sensors. A goal of this demonstration was the acquisition of a complete, controlled set of data for model development, training, and sensor fusion.

Test Matrix A description of the test matrix follows. Table 2, lists the ordnance items proposed for testing and the depths and orientations at which signatures were to be collected using the magnetometer array. The depths range from the maximum probable depth that an individual item is likely to be found upward in convenient steps. Also listed in Table 2 are the planned E-W survey widths and the magnetometer

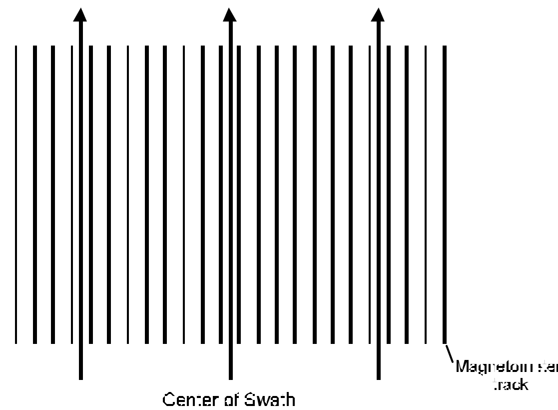

Figure 6. Example of a 5.75 m wide survey consisting of three passes of the *MTADS* Tow Platform. The long vertical lines (with arrowheads) denote the tow vehicle paths and the other vertical lines trace the individual sensor tracks.

spacings. All surveys were conducted in a S-N direction because of restrictions at the site. The standard magnetometer horizontal spacing is 0.25 m (resulting in a total array width of 1.75 m). Combined with a lane spacing of 2 m, this results in E-W survey widths of 1.75, 3.75, *etc.* An illustration of a 5.75 m wide survey is shown in Figure 10.

Figure 5. Test ordnance placed for signature acquisition in the *MTADS* test pit.

Table 2. Proposed Magnetometer Test Matrix for Ordnance Signature Acquisition.

Ordnance Item	Depths (m)	E-W Survey Width (m)	Mag Spacing (cm)	Azimuth Steps	Inclination Steps
20 mm Projectile	surface	1.875	12.5 cm	N/A	N/A
30 mm Projectile	surface	1.875	12.5 cm	N/A	N/A
M42 Grenade	0.15 & surface	1.875	12.5 cm	N/A	N/A
M46 Submunition	0.15 & surface	1.875	12.5 cm	N/A	N/A
60 mm Mortar	1¼, 1, ¾, ½	3.75	25 cm	22.5°	22.5°
2.75" Rocket	1½, 1¼, 1, ¾	3.75	25 cm	22.5°	22.5°
81 mm Mortar	2, 1½, 1¼, 1, ¾	5.75	25 cm	22.5°	22.5°
105 mm Projectile	3, 2½, 2, 1½, 1	7.75	25 cm	22.5°	22.5°
4.2" Mortar	3, 2½, 2, 1½, 1	7.75	25 cm	22.5°	22.5°
5" Rocket	3, 2½, 2, 1½, 1	7.75	25 cm	22.5°	22.5°
155 mm Projectile	3½, 3, 2½, 2, 1½	9.75	25 cm	22.5°	22.5°
Mk 82 500 lb Bomb	6, 4½, 3,1½	13.75	25 cm	22.5°	22.5°
Mk 83 1000 lb Bomb	6, 4½, 3, 1½	13.75	25 cm	22.5°	22.5°

Figure 7. Samples of the inert ordnance items available to the *MTADS* program.

Table 4 shows the planned ordnance test matrix for the EM sensor array. Table 5 presents the priority measurements made using this platform.

Table 3. Priority Magnetometer Measurements

Ordnance Item	Depths (m)	E-W Survey Width (m)	Mag Spacing (cm)	Azimuth	Inclination
20 mm projectile	surface	1.75	25	0˚, 90°	0˚
30 mm projectile	surface	1.75	25	0˚, 90°	0˚
M42 grenade	surface, 0.15	1.75	25	0˚, 90°	0˚
M46 submunition	surface, 0.15	1.75	25	0˚, 90°	0˚
60 mm mortar	0.25, 0.5	5.75	25	45° steps	45° steps
81 mm mortar	0.5, 0.75, 1.0	5.75	25	45° steps	45° steps
105 mm projectile	0.5, 0.75, 1.0	9.75	25	45° steps	45° steps
5" rocket	1.0, 1.5	9.75	25	45° steps	45° steps
250 lb bomb	2.0, 3.5	13.75	25	90° steps	90° steps
Mk 82 500 lb bomb	2.0, 3.5, 5.5	13.75	25	90° steps	90° steps

Table 4. Proposed EM-61 Test Matrix for Ordnance Signature Acquisition

Ordnance Item	Depths (m)	E-W Survey Width (m)	Azimuth Steps	Inclination Steps
20 mm projectile	surface	2	90°	N/A
30 mm projectile	surface	2	90°	N/A
M42 grenade	0.15 & surface	2	90°	N/A
M46 submunition	0.15 & surface	2	90°	N/A
60 mm mortar	1, ¾, ½	6	45°	45°
2.75" rocket	1, ¾	6	45°	45°
81 mm mortar	1, ¾	6	45°	45°
105 mm projectile	1, ½	10	45°	45°
4.2" mortar	1	10	45°	45°
5" rocket	1	10	45°	45°

Table 5. Priority EM-61 Measurements

Ordnance Item	Depths (m)	E-W Survey Width (m)	Azimuth Steps	Inclination Steps
20 mm projectile	surface	1	90°	N/A
30 mm projectile	surface	1	90°	N/A
M42 grenade	surface, 0.15	2	90°	N/A
M46 submunition	surface, 0.15	2	90°	N/A
60 mm mortar	0.25, 0.5, 0.75, 1.0	6	90°	90°
81 mm mortar	0.5, 0.75, 1.0	6	90°	90°
105 mm projectile	0.5, 0.75, 1.0, 1.25	10	90°	90°
5" rocket	0.5, 1.0, 1.5	10	90°	90°
155 mm projectile	1.5, 2.0	10	90˚	90˚

The results of this series of measurements were documented in two ways. First, the standard series of *MTADS* DAQ output files was archived. These consist of the root file name constructed as YYDDDTTT, where YY is the last two digits of the year, DDD is the Julian date, and TTT is the fraction of day in 1/1000's. The four standard files are .SID, .GPS, .ADU, and .MAG or .EM. In addition, an ASCII file of x, y, intensity -- where intensity is total field, vertical gradient or pairs of EM-61 readings -- was constructed. The ASCII files were named IDDDAAII.dat, where I is a one-letter ordnance identifier, DDD is depth in cm, and AA and II are azimuth and inclination in 16ths of a circle. These files should be usable by any data analysis or modeling program.

The *MTADS* data analyses of the ordnance signatures result in several evaluations: (1) graphics images of the experimental target data with a comparison with the modeled target fits are generated and presented to the analyst; (2) target model fit criteria are presented to the analyst along with a “goodness of fit” evaluation (these data are entered into survey target tables); and (3) a graphic image of the boxed target area overlaid on the site view screen is presented to the analyst. Item (3) can be annotated and edited and used to create a Post Script file for printing or archiving. This information was used prior to Demonstration 2 to refine the analysis algorithms in the DAS.

5.0 PERFORMANCE ASSESSMENT

Since there were several objectives of this demonstration, the results fall into different classes. The checks against the performance criteria listed in Table 1 result in Pass/Fail declarations. The target signature acquisition and analysis result in more quantitative results such as miss distance, depth error, etc. Each of these test categories is discussed below.

5.1 TECHEVAL Performance Criteria

Table 6 summarizes the performance of the system against the various design criteria. As can be seen, the *MTADS* system successfully met most design goals at TECHEVAL. The areas in which we were unsuccessful and the improvements/fixes planned are discussed individually below.

The most prominent shortcoming of the system involved the dead-reckoning system which was designed to provide location and guidance during periods of GPS unavailability. This system comprises an on-platform electronic compass for recording vehicle direction and tick wheels on both Tow Vehicle drive wheels for recording progress down the track. We found in the demonstration that the compass reading exhibits a moderate deviation on straight portions of the survey and is unreliable in turns. Additionally, the tick wheel readings are noisy. These two data

deficiencies

Table 6. TECHEVAL Performance Results

Subsystem	Requirement	Evaluation Criteria	Pass?
DAQ	Sensor Data Streams	Correctly formats and time stamps all data	✓
	Survey Land Marking	Incorporates both static and dynamic landmarks	✓
	Survey Planning	Sets up survey grid based upon landmark data	✓
	Survey Guidance	Displays real-time survey progress map	✓
		Displays heading and off-track information	✓
		Correctly displays degrading from RTK to DGPS to DR	✓
		Correctly displays missed areas and guides the survey operator	×
	Target Landmarking	Sets up scheme and directs target reacquisition and marking, allowing waypointing 5 acres/day with 20 targets/acre	✓
	Survey	Accommodates 8 hours of survey data Correctly prepares output files for download	✓
Navigation	Operational Position Accuracy	(x,y < 0.03 m, z < 0.05 m)	✓
	Dead-Reckoning Sensors	Incorporate data into Navfill, maintaining position accuracy during RTK holidays of up to 20 s, using inertial navigation and compass aids	×
	Reference Station	Supports Mobile Unit using RF Repeaters	✓
Field Hardware	Tow Vehicle	Ability to support vehicle, DAQ, and all sensors for 8 hours on internal batteries without recharge and will accommodate 4 hours of continuous data collection	✓
	Magnetometers	Demonstrate performance against procurement specs when deployed as magnetometer and gradiometer arrays	✓
	EM Sensors	Successfully demonstrate performance against procurement specs when deployed as an overlapping array	✓
DAS	Preprocessing	Correctly merges all landmark, sensor, navigation, and reference files	✓
		Generates all necessary navigation and noise spectra plots	✓
		Incorporates commercial software to post process data during loss of radio link while surveying	×

Table 6. TECHEVAL Performance Results

Subsystem	Requirement	Evaluation Criteria	Pass?
		Successfully produces all necessary navigation editing and corrections	✓
		Successfully performs all expert sensor data correction modules	✗
	Processing	Analyzes all targets for location, depth, and size within specs for all sensor arrays	✓
		Demonstrates ability to locate targets in a large gradient offset using the gradiometer system	✓
		Demonstrates the ability to correctly analyze large targets in the presence of surface clutter	✓
		Provides specified output files for DAQ to landmark targets	✗
		Provides required output graphics and tables correctly formatted and font and color corrected	✓
		Demonstrates an analysis system to successfully correlate multisensor data sets	✓
		Demonstrates ability to create topographic maps correlated with magnetic anomaly mapping	✗
		Demonstrate graphic output capability compatible with GIS format requirements	✗

in turn hampered the DAS developers' ability to correctly use the dead-reckoning information to calculate sensor location. The planned improvements include a careful measurement and minimization of the compass deviation and incorporation of an improved technique for measuring the tick wheel count to decrease the noise. This last point can only be partially resolved since motion of the Tow Vehicle over rough terrain is necessarily jerky. With these improvements to the dead-reckoning data, the DAS developers will focus on incorporating these data into the sensor location calculations.

Another significant shortcoming in the system capabilities involves the production of a target list for waypointing and the communication of that list to the guidance system in the Tow Vehicle. We have not yet solved the format and communication hang-ups associated with this function. The next two demonstration do not involve actual target marking in the field but we plan to use those demonstrations to separately test our progress in this area.

We have not satisfactorily completed the Tow Vehicle guidance system. The GPS receiver used for the CBD demonstration has a significant latency between position fix and communicating that fix to the guidance system. In addition, there is some delay in mapping that position to the operator's screen. These two delays combine to make it very difficult to use the survey guidance system as intended. The ESTCP Program Office provided funds for, and we have ordered, an updated GPS receiver that reduces the position reporting latency from 3 seconds to 0.2 seconds. We have also undertaken a program to minimize the mapping latency in the guidance software. These two together should allow us to demonstrate satisfactory guidance at Demonstration 2 at

Twentynine Palms.

The final three deficiencies are attributable to running out of of time before this demonstration. The DAS development has three items that remain to be completed. Some of the expert modules for sensor data correction are not yet active. These do not affect the ability of the system to analyze target data, as will be seen in the next section. They might come into play later at sites that have particularly difficult magnetic backgrounds, such as large interference from nearby buildings. We have not yet completed the portions of the code that generate topographic maps and that output our signature data in a GIS-compatible format. All of these topics are under active development and we expect them to be completed by the last demonstration.

5.2 Ordnance Signature Collection

Using both the magnetometer platform and the EM platform, 164 individual ordnance signatures were collected and 139 of those were analyzed by the *MTADS* DAS. Table 7 details the results of the fits of the magnetometer signatures and Table 8 details those of the EM signatures. Overall, both the precision of the fits and location accuracy recovered from the fits were quite good. As expected, individual ordnance items displayed different maximum detection depths for the two sensor arrays.

Magnetic Signatures The *MTADS* fit algorithm displayed good dipole fits in all cases tested. Overall the "goodness of fit" parameter ranged from 0.821 to 0.996. When it falls below 0.97, the average error in the fit location and depth is observed to increase. Individual cases with lower fit parameters fall into three categories: shallow ordnance where the spatial extent of the magnetic signal was on the order of the horizontal sensor spacing; ordnance signatures with low signal-to-noise ratio (SNR); and deep objects where the anomaly signal extended outside of the measured area. For well-measured, strong SNR cases (>20 nT), the "goodness of fit" parameter ranged from 0.969 to 0.996 with an average value of 0.988. These magnetic anomaly signatures are well described by a magnetic dipole signal. Subtraction of the modeled dipole signal from the measured data left no coherent residual signal that would indicate higher order magnetic moments in the magnetic signature.

The standard deviation in the (Δx, Δy) location errors was 0.05 m for the high SNR objects. This is on the order of the accuracy of the GPS system by itself. For the lower SNR (10 to 20 nT peak anomalies) objects, location errors were 0.10 m. The shallow ordnance had larger location errors in x (0.08 m) than in y (0.04 m). All of the data were collected with the vehicle driving in the y direction; so, the sensor sampling was effectively 0.25 m in the x direction (array spacing) and 0.06 m in the y direction. The deep ordnance had the largest standard deviation in the location errors, on the order of 0.40 m. The spatial extent of these signatures extended well outside of the survey area and this presumably contributed to the location error. For the entire magnetometer data set, the average offset of the fitted position was 15 cm.

The estimate of the dipole's vertical distance beneath the sensors is plotted against the actual distance (the sensor array was 0.25 m above the ground) of the ordnance in Figure 12. The dipole fitting algorithm gives very accurate depth estimates. The standard deviation in the relative depth errors ($\Delta z/z$) is 0.06. The largest relative depth errors are about 0.18 and occur for both the shallow and deep targets.

The strength of the estimated dipole moment is plotted versus ordnance diameter in Figure 13. The line shows the predicted dipole moment based on equating

the volume of the ordnance to the volume of a sphere

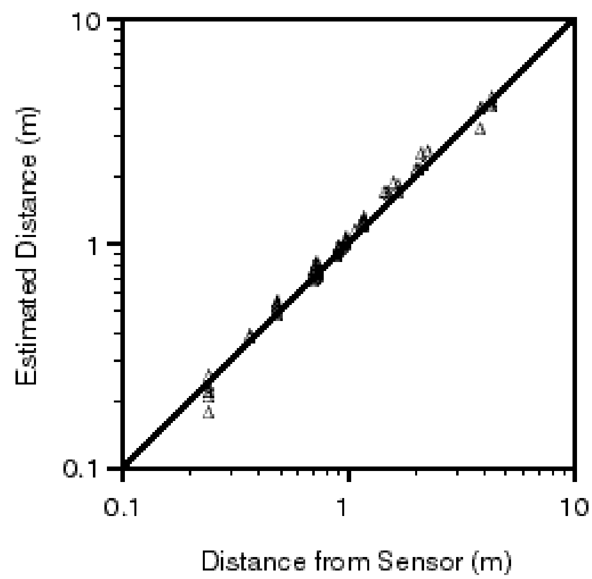

Figure 12. *MTADS* DAS estimate of test ordnance distance below the magnetometer array vs. the actual distance

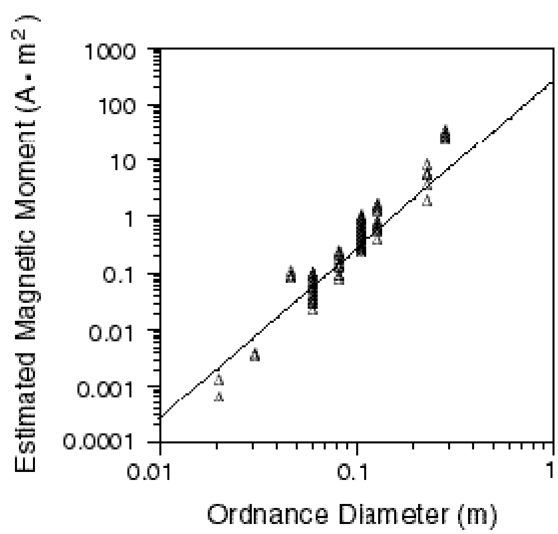

Figure 13. DAS estimated dipole moment strength vs. actual ordnance diameter

Table 7. *MTADS* Analysis of Magnetic Signatures of Test Ordnance

Test Setup				*MTADS* DAS Analysis							
Item	Depth (m)	Azimuth (˚)	Inclin. (˚)	Depth (m)	X (cm)	Y (cm)	Azimuth (˚)	Inclin. (˚)	Moment (A•m^2)	Size (m)	Fit Quality
20 mm projectile	surface	0	0	0.02	-4	2	13	10	0.00	0.02	0.41
20 mm projectile	surface	90	0	0.01	-14	-1	329	69	0.00	0.01	0.44
30 mm projectile	surface	0	0	0.00	-21	-1	92	127	0.00	0.01	0.53
30 mm projectile	surface	90	0	0.00	-19	-1	80	126	0.00	0.01	0.49
M46 submunition	surface	0	0	0.00	-5	3	185	-13	0.08	0.06	0.99
M46 submunition	13 cm	0	0	0.14	-3	2	350	-13	0.09	0.06	0.99
M46 submunition	13 cm	90	0	0.14	-5	5	80	-8	0.09	0.06	0.99
60 mm mortar	0.26	0	0	0.20	2	10	334	36	0.04	0.04	0.92
60 mm mortar	0.26	45	0	0.17	10	8	30	47	0.02	0.04	0.83
60 mm mortar	0.26	90	0	0.13	16	7	100	52	0.01	0.03	0.68
60 mm mortar	0.26	135	0	0.12	3	6	280	44	0.01	0.03	0.74
60 mm mortar	0.26	180	0	0.15	2	7	313	21	0.02	0.03	0.54
60 mm mortar	0.25	0	45	0.22	3	7	309	55	0.07	0.05	0.96
60 mm mortar	0.25	45	45	0.24	8	6	17	74	0.06	0.05	0.95
60 mm mortar	0.25	90	45	0.26	6	1	252	97	0.05	0.05	0.92
60 mm mortar	0.25	135	45	0.23	3	-2	157	59	0.04	0.04	0.89
60 mm mortar	0.25	180	45	0.26	5	-2	175	53	0.04	0.04	0.91

Table 7. *MTADS* Analysis of Magnetic Signatures of Test Ordnance

Test Setup				*MTADS* DAS Analysis							
Item	Depth (m)	Azimuth (˚)	Inclin. (˚)	Depth (m)	X (cm)	Y (cm)	Azimuth (˚)	Inclin. (˚)	Moment (A•m^2)	Size (m)	Fit Quality
60 mm mortar	0.25	0	90	0.26	4	3	23	104	0.09	0.06	0.97
60 mm mortar	0.50	0	0	0.25	2	25	347	177	0.01	0.03	0.64
60 mm mortar	0.50	45	0	0.53	18	3	68	30	0.04	0.04	0.63
60 mm mortar	0.50	135	0	1.18	2	11	90	180	0.19	0.07	0.51
60 mm mortar	0.50	180	0	1.01	19	90	250	-20	0.12	0.06	0.44
60 mm mortar	0.51	0	45	0.37	15	4	16	52	0.04	0.04	0.80
60 mm mortar	0.51	90	45	0.32	12	6	87	58	0.02	0.03	0.56
60 mm mortar	0.51	135	45	0.66	3	-10	152	25	0.06	0.05	0.71
60 mm mortar	0.51	180	45	0.64	-1	-1	192	11	0.04	0.05	0.43
60 mm mortar	0.51	0	90	0.49	2	3	342	99	0.07	0.05	0.71
81 mm mortar	0.51	0	0	0.42	4	8	323	54	0.05	0.05	0.86
81 mm mortar	0.51	45	0	0.53	26	12	61	56	0.07	0.05	0.79
81 mm mortar	0.51	90	0	0.53	4	8	266	31	0.09	0.06	0.79
81 mm mortar	0.51	135	0	0.46	6	8	299	21	0.12	0.06	0.87
81 mm mortar	0.51	180	0	0.43	7	9	345	30	0.12	0.06	0.94
81 mm mortar	0.50	0	45	0.48	6	6	342	67	0.17	0.07	0.97
81 mm mortar	0.50	45	45	0.49	7	5	21	71	0.16	0.07	0.96

Table 7. *MTADS* Analysis of Magnetic Signatures of Test Ordnance

Test Setup				*MTADS* DAS Analysis							
Item	Depth (m)	Azimuth (˚)	Inclin. (˚)	Depth (m)	X (cm)	Y (cm)	Azimuth (˚)	Inclin. (˚)	Moment (A•m^2)	Size (m)	Fit Quality
81 mm mortar	0.50	90	45	0.50	4	-4	135	76	0.12	0.06	0.93
81 mm mortar	0.50	135	45	0.43	9	-3	142	64	0.06	0.05	0.88
81 mm mortar	0.50	180	45	0.75	-12	-4	229	43	0.13	0.07	0.73
81 mm mortar	0.50	0	90	0.50	6	4	186	69	0.20	0.08	0.97
81 mm mortar	0.73	45	0	0.74	10	-1	83	136	0.05	0.05	0.47
81 mm mortar	0.76	135	0	0.65	9	11	308	8	0.12	0.06	0.82
81 mm mortar	0.76	180	0	0.67	10	-5	327	26	0.12	0.06	0.72
81 mm mortar	0.74	0	45	0.61	14	21	357	37	0.09	0.06	0.87
81 mm mortar	0.74	45	45	0.75	-5	12	146	125	0.09	0.06	0.64
81 mm mortar	0.75	0	90	0.72	9	-13	249	67	0.13	0.07	0.68
81 mm mortar	0.85	0	45	0.74	10	-4	164	105	0.09	0.06	0.75
81 mm mortar	0.97	0	90	0.90	16	29	3	75	0.09	0.06	0.65
105 mm projectile	0.49	0	0	0.48	8	2	351	39	0.39	0.09	0.96
105 mm projectile	0.49	45	0	0.48	2	-1	27	56	0.31	0.09	0.92
105 mm projectile	0.49	90	0	0.47	4	1	307	78	0.21	0.08	0.97
105 mm projectile	0.49	135	0	0.48	2	6	310	35	0.38	0.09	0.98
105 mm projectile	0.49	180	0	0.42	3	6	349	35	0.38	0.09	0.86

Table 7. *MTADS* Analysis of Magnetic Signatures of Test Ordnance

Test Setup				*MTADS* DAS Analysis							
Item	Depth (m)	Azimuth (˚)	Inclin. (˚)	Depth (m)	X (cm)	Y (cm)	Azimuth (˚)	Inclin. (˚)	Moment (A•m^2)	Size (m)	Fit Quality
105 mm projectile	0.50	45	45	0.50	3	-4	48	71	0.93	0.13	0.99
105 mm projectile	0.50	90	45	0.53	6	1	85	58	0.85	0.12	0.97
105 mm projectile	0.50	135	45	0.52	2	5	305	113	0.61	0.11	0.97
105 mm projectile	0.50	180	45	0.47	6	10	174	64	0.53	0.10	0.97
105 mm projectile	0.49	0	90	0.47	6	4	4	103	1.09	0.13	0.99
105 mm projectile	0.70	0	0	0.67	6	4	352	37	0.37	0.09	0.97
105 mm projectile	0.70	90	0	0.69	15	1	5	86	0.19	0.07	0.87
105 mm projectile	0.70	135	0	0.69	-8	7	317	29	0.27	0.08	0.76
105 mm projectile	0.70	180	0	0.74	11	8	356	35	0.48	0.10	0.86
105 mm projectile	0.70	0	45	0.70	6	-3	345	69	0.95	0.13	0.98
105 mm projectile	0.70	135	45	0.72	9	8	117	58	0.55	0.11	0.96
105 mm projectile	0.70	180	45	0.73	7	8	180	73	0.45	0.10	0.94
105 mm projectile	0.73	0	90	0.70	14	10	140	80	0.95	0.13	0.97
105 mm projectile	1.32 m	0	90	1.34	7	-9	150	69	0.75	0.12	0.95
5" rocket	0.95	0	0	1.04	12	1	359	40	0.78	0.12	0.95
5" rocket	0.95	45	0	1.14	14	-3	43	46	0.80	0.12	0.93
5" rocket	0.95	90	0	1.10	2	-1	330	83	0.46	0.10	0.88

Table 7. *MTADS* Analysis of Magnetic Signatures of Test Ordnance

Test Setup				*MTADS* DAS Analysis							
Item	Depth (m)	Azimuth (˚)	Inclin. (˚)	Depth (m)	X (cm)	Y (cm)	Azimuth (˚)	Inclin. (˚)	Moment ($A \bullet m^2$)	Size (m)	Fit Quality
5" rocket	0.95	135	0	1.30	32	-16	346	75	0.76	0.12	0.87
5" rocket	0.95	180	0	1.21	4	-2	333	44	0.91	0.12	0.81
5" rocket	0.76	0	45	0.84	9	3	345	67	1.59	0.15	0.98
5" rocket	0.76	45	45	0.88	14	3	54	59	1.66	0.15	0.97
5" rocket	0.76	90	45	0.89	12	6	81	54	1.46	0.15	0.91
5" rocket	0.76	135	45	0.88	17	10	104	57	1.02	0.13	0.92
5" rocket	0.76	180	45	0.74	11	-5	165	49	0.67	0.11	0.91
5" rocket	0.86	0	90	0.90	4	-8	90	80	1.45	0.15	0.88
5" rocket	1.50 m	0	90	1.52	0.46	0.21	78	46	1.47	0.15	0.82
250 lb bomb	2.10 m	180	0	2.49	0.46	-0.44	129	58	3.49	0.20	0.96
250 lb bomb	2.05 m	0	90	2.45	0.36	-0.22	20	48	6.00	0.23	0.95
500 lb bomb	1.85 m	0	60	1.96	19	-37	1.5	86	35.80	0.42	0.98
500 lb bomb	1.85 m	90	60	1.94	-15	-11	112	70	30.20	0.40	0.99
500 lb bomb	4.23 m	0	60	3.78	33	-86	200	75	21.40	0.36	0.97
500 lb bomb	4.13 m	90	60	4.02	67	-17	167	91	24.50	0.37	0.96
500 lb bomb	5.42 m	0	60	4.34	75	-119	165	55	15.90	0.32	0.93
500 lb bomb	5.42 m	90	60	5.30	-16	16	150	85	24.20	0.37	0.92

Table 8. *MTADS* Analysis of EM Signatures of Test Ordnance

Test Setup				*MTADS* DAS Analysis					
Item	Depth (m)	Azimuth (˚)	Inclin. (˚)	Depth (m)	X (cm)	Y (cm)	Ferrous Size (m)	Non-Ferrous Size (m)	Fit Quality
20 mm projectile	surface	0	0	0.00	4	42	0.01	0.01	0.08
20 mm projectile	surface	90	0	0.00	6	-15	0.01	0.01	0.08
30 mm projectile	surface	0	0	0.00	3	-26	0.02	0.02	0.81
30 mm projectile	surface	90	0	0.00	-3	-3	0.02	0.02	0.77
M42 grenade	surface	0	0	0.00	-6	-14	0.03	0.03	0.88
M42 grenade	surface	90	0	0.00	-3	2	0.02	0.02	0.86
M42 grenade	0.12 m	0	0	0.00	-2	-8	0.02	0.02	0.81
M42 grenade	0.12 m	90	0	0.00	-5	0	0.02	0.02	0.79
M46 submunition	surface	0	0	0.00	-1	-8	0.02	0.02	0.85
M46 submunition	surface	90	0	0.00	-7	1	0.02	0.02	0.89
M46 submunition	0.12 m	0	0	0.00	-5	-30	0.02	0.02	0.65
M46 submunition	0.12 m	90	0	0.00	-5	-7	0.02	0.02	0.69
60 mm mortar	0.25 m	0	0	0.39	-1	7	0.07	0.13	0.91
60 mm mortar	0.25 m	90	0	0.00	1	4	0.04	0.05	0.97
60 mm mortar	0.23 m	0	90	0.00	4	-3	0.04	0.07	0.93
60 mm mortar	0.49 m	0	0	0.57	7	9	0.06	0.11	0.84
60 mm mortar	0.49 m	90	0	0.35	-5	-10	0.04	0.07	0.74
60 mm mortar	0.51 m	0	90	0.00	5	-10	0.04	0.05	0.92

Table 8. *MTADS* Analysis of EM Signatures of Test Ordnance

Test Setup				*MTADS* DAS Analysis					
Item	Depth (m)	Azimuth (˚)	Inclin. (˚)	Depth (m)	X (cm)	Y (cm)	Ferrous Size (m)	Non-Ferrous Size (m)	Fit Quality
60 mm mortar	0.75 m	0	0	0.55	1	-13	0.04	0.06	0.25
60 mm mortar	0.75 m	90	0	0.08	3	0	0.02	0.02	0.32
60 mm mortar	0.75 m	0	90	0.22	-1	11	0.04	0.05	0.82
60 mm mortar	1.01 m	0	0	0.00	1	6	0.01	0.01	0.03
60 mm mortar	1.01 m	90	0	-0.01	-1	24	0.01	0.01	0.01
60 mm mortar	1.01 m	0	90	0.19	-8	9	0.03	0.03	0.40
81 mm mortar	0.49 m	0	0	0.39	0	10	0.07	0.13	0.96
81 mm mortar	0.49 m	90	0	0.42	16	-3	0.07	0.14	0.91
81 mm mortar	0.50 m	0	90	0.18	19	4	0.06	0.11	0.90
81 mm mortar	0.76 m	0	0	0.68	-1	-3	0.07	0.13	0.90
81 mm mortar	0.76 m	90	0	0.36	-6	9	0.05	0.07	0.77
81 mm mortar	0.74 m	0	90	0.18	2	10	0.05	0.07	0.95
81 mm mortar	0.99 m	0	0	0.67	-8	-16	0.05	0.09	0.58
81 mm mortar	0.99 m	90	0	0.58	1	-12	0.05	0.07	0.53
81 mm mortar	0.97 m	0	90	0.48	-3	-2	0.05	0.08	0.88
105 mm projectile	0.49 m	0	0	0.34	0	-9	0.09	0.20	0.99
105 mm projectile	0.49 m	90	0	0.28	-4	-2	0.08	0.17	0.99
105 mm projectile	0.50 m	0	90	0.17	1	9	0.07	0.16	0.99

Table 8. *MTADS* Analysis of EM Signatures of Test Ordnance

Test Setup				*MTADS* DAS Analysis					
Item	Depth (m)	Azimuth (˚)	Inclin. (˚)	Depth (m)	X (cm)	Y (cm)	Ferrous Size (m)	Non-Ferrous Size (m)	Fit Quality
105 mm projectile	0.75 m	0	0	0.54	-1	-8	0.08	0.17	0.96
105 mm projectile	0.75 m	90	0	0.47	-1	-2	0.07	0.15	0.96
105 mm projectile	0.76 m	0	90	0.38	0	3	0.07	0.14	0.98
105 mm projectile	0.98 m	0	0	0.52	5	-2	0.06	0.11	0.90
105 mm projectile	0.91 m	0	90	0.47	-3	-5	0.07	0.13	0.96
105 mm projectile	1.34 m	90	0	0.53	-10	-13	0.04		0.26
5" rocket	0.48 m	0	0	0.29	1	11	0.09	0.22	0.98
5" rocket	0.48 m	90	0	0.26	-2	5	0.09	0.21	0.99
5" rocket	0.48 m	0	90	0.35	0	1	0.10	0.24	0.97
5" rocket	0.97 m	0	0	0.65	5	-8	0.08	0.18	0.86
5" rocket	0.97 m	90	0	0.57	-1	-8	0.07	0.16	0.94
5" rocket	1.5 m	0	0	0.91	9	-8	0.60		0.55
5" rocket	1.5 m	90	0	1.11	2	-4	0.70		0.34
5" rocket	1.65 m	0	90	1.72	3	-35	0.90		0.13
155 mm projectile	1.6 m	90	0	1.36	1	-7	1.00		0.63
155 mm projectile	1.9 m	0	90	1.63	-6	16	0.90		0.29

and calculating the induced dipole moment for this equivalent sphere. The *MTADS* fitting algorithm estimates size based on this equivalent sphere model. The estimated dipole moments show significant variation for a given object. As the 105 mm projectile at 0.5 m depth is varied through 11 orientations, its estimated moment varies from 0.254 to 1.02 Amps-m^2. Table 9 presents the variation in estimated moments for the 60 mm mortar, the 81 mm mortar, the 105 mm projectile, and the 5” rocket over various orientations and depths. The result this has on the effective size calculated is shown for each. For the 105 mm projectile, the calculated effective size ranges from 100 mm to 163 mm. Using this effective size estimate, it is not possible to uniquely resolve ordnance items of similar size.

Both the strength and the direction of the dipole moment changes as the orientation of the ordnance changes relative to the Earth’s field. Figure 14 shows magnetic anomaly images for a 105 mm projectile 0.5 m deep at four different orientations. All four observed magnetic dipoles are oriented towards magnetic north. When the long dimension of the ordnance is aligned with east-west, the dipole strength is significantly weaker.

To model the complex behavior of the dipole moment as a function of ordnance orientation, a prolate spheroidal model has been suggested.[18] The induced dipole moment predicted by this model is a function of the length of the major and minor axes of the spheroid and the orientation of the spheroid relative to the Earth’s magnetic field. In Figure 15, (a) the magnitude of the dipole moment, (b) the azimuth angle of the moment, and (c) the inclination angle of the moment are plotted as a function of the azimuthal direction of the horizontal 105 mm projectile at the depths of 0.5 m (plus symbols) and 0.98 m (diamonds). The azimuth angle used here is defined counter-clockwise from the x axis. The inclination angle is defined as positive pointed down from the horizontal x-y plane. Magnetic north has an azimuth angle of 100 degrees and an inclination of 68 degrees at the test site. The curves in each figure indicate the predicted moments for a prolate spheroid 0.105 m in diameter and 0.389 m in length. There is reasonable agreement with the measured dipole moments. It should be noted that the actual 105 mm projectile is flat on one end and pointed on the other. It is interesting to note that when the ordnance is pointing to the north its dipole moment is weaker than when it is pointing to the south. For the symmetric spheroid, both orientations produce the same moment.

Table 9. Estimated Moments and Effective Sizes of Ordnance from the *MTADS* DAS

Ordnance	Average Moment (Amps-m^2)	Moment Range (Amps-m^2)	Average Size (mm)	Size Range (mm)
60 mm	0.0583	0.0235 - 0.104	60	45 - 74
81 mm	0.158	0.0767-0.259	84	67 - 101
105mm	0.610	0.254-1.10	132	100 - 163
5” (127mm)	0.957	0.415-1.63	153	118 - 186

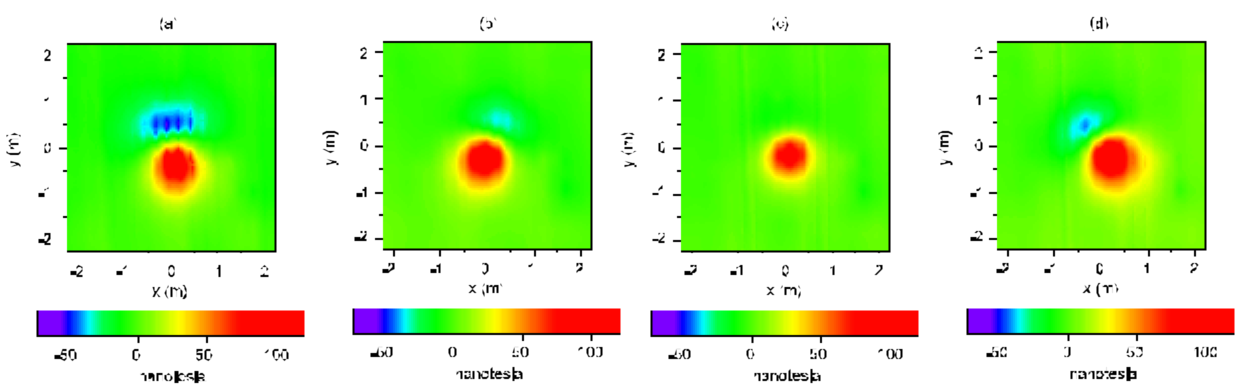

Figure 14. Observed magnetic signatures of a 105 mm projectile 0.5 m deep oriented with an inclination of 0˚ and an azimuth of a) 0˚, b) 45˚, c) 90˚, and d) 135˚

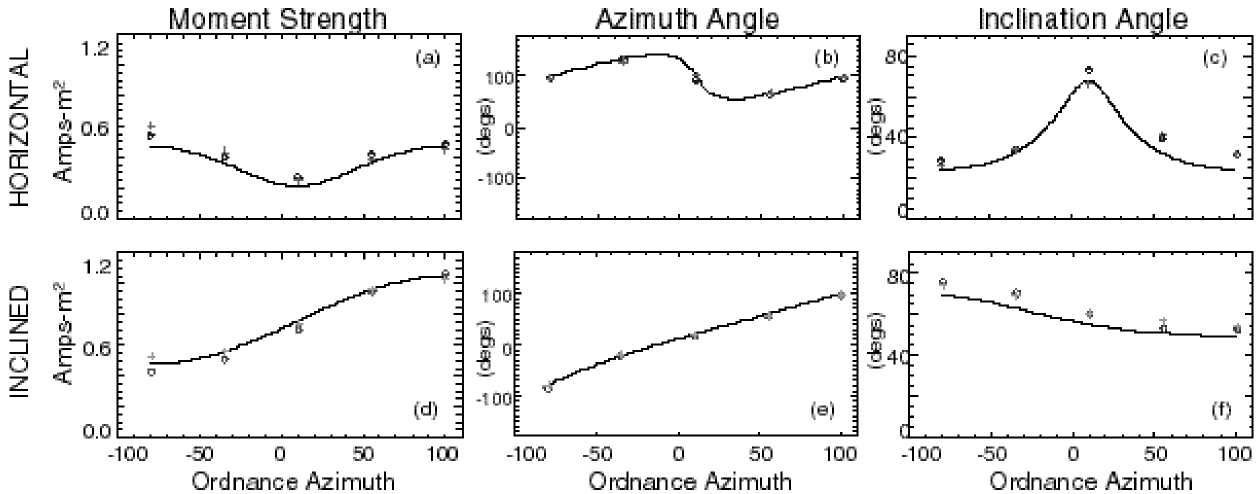

Figure 15. Dipole moment parameters of (a) magnitude, (b) azimuth, and (c) inclination as a function of actual azimuth of a 105 mm projectile with an inclination of 0˚ and dipole moment parameters of (d) magnitude, (e) azimuth, and (f) inclination as a function of actual azimuth of a 105 mm projectile with and inclination of 45˚

Besides the effect of shape, another possible explanation for this could be a small remnant magnetization along the axis of the ordnance. Plotted in the lower three panels of Figure 15 are the same dipole parameters as a function of ordnance azimuthal orientation for the 105 mm inclined at 45^{o}. The two depths are at 0.5 m (plus) and 0.7 m (diamonds). Again, there is reasonable agreement with the prolate spheroid model.

From the magnetic signatures of the ordnance used in this test set, it is only possible to measure a dipole signal and determine the parameters of this dipole. While the location and depth of this dipole can be used to accurately determine the ordnance location, the strength and orientation of the dipole can not be used to uniquely determine its diameter, length, and orientation. An effective size can be estimated that has a range of overlap with similar sized ordnance.

Induced EM Signatures As in the case of the magnetic signatures, all EM signatures collected in this demonstration were well fit by the *MTADS* DAS. Surprisingly, the offset distances were similar to, and in some cases smaller than, those found in the case of the magnetic signatures. This is true even though the antenna size is 1 m^2 and the along track sampling rate is ~2.5 smaller for the EM platform. The average miss distance for the entire set was 11 cm. This EM data set

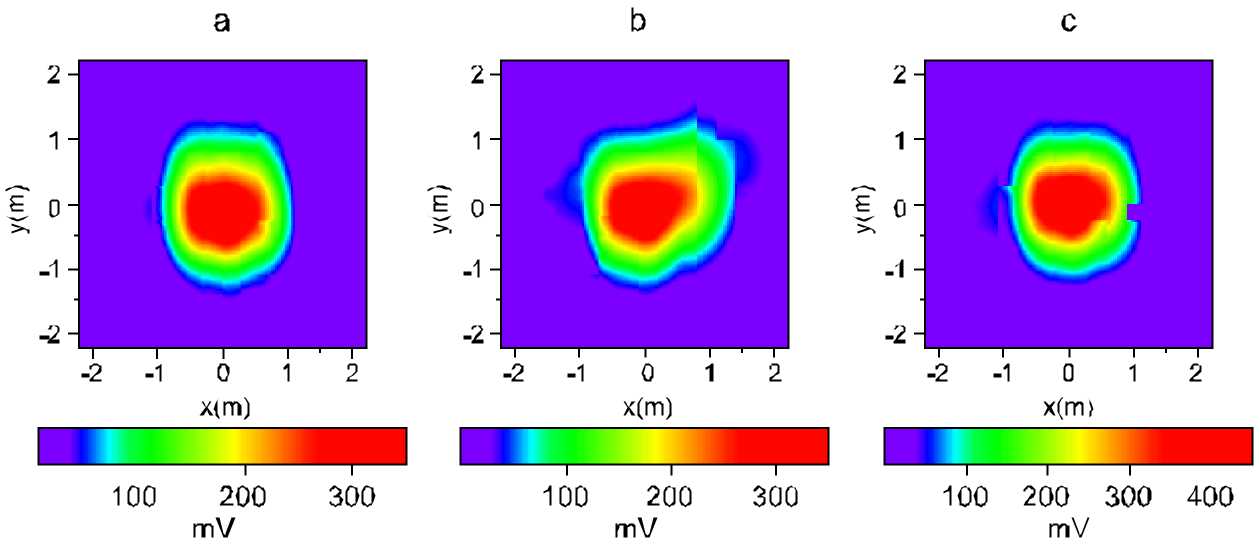

Figure 16. Measured EM signature from a 105 mm projectile 0.75 m deep at (a) azimuth 0˚, inclination 0˚; (b) azimuth 90˚, inclination 0˚; and (c) azimuth 0˚, inclination 90˚

does not include many of the bigger, deeper items that increased the average distance for the magnetometer test set.

The EM signature of a 105 mm projectile 0.75 m deep is shown for three orientations in Figure 16. In this presentation, the signatures look remarkably similar although the peak value for the projectile pointing down is stronger than for the other two orientations. To investigate more thoroughly the orientation dependence of the EM signatures, we calibrated our model using a spherical object.

The measured signal from the center EM sensor as it passes over a spherical 16 lb. ferrous shot-put that is 0.25 m below the surface is shown in Figure 17. The symbols represent measured data points and the curve is the model result from the fit algorithm. The model predicts the correct signal shape, signal amplitude, and relative amplitude between the upper and lower coils.

The EM sensor array has the sensitivity to detect a range of small and intermediate ordnance at depths below the detection limit of the magnetometer array. However, while the EM fit algorithm based on the sphere model was found to be effective for spherical objects, it was not as effective at predicting the signal shape or amplitude of elongated ordnance. Figure 18 shows the estimated distance below the EM sensor obtained from the EM fit algorithm versus the actual distance while Figure 19 shows the corresponding comparison of ordnance size. As can be seen from these two figures, there is significant deviation in the estimated parameters.

At any depth, the measured ordnance signal was found to vary significantly from the sphere model as a function of the ordnance orientation relative to the direction of travel of the EM array. Figure 20 plots the measured signal from a 2.75” rocket that is 0.25 m below the surface oriented (a) vertically, (b) horizontally along the direction of travel, and (c) horizontally across the direction of travel (the diamonds are the measured data points). The sphere model does not account for object orientation and would return the signal shape shown in Figure 17 for the shot-put. The spherical shot-put has an effective volume similar to the rocket and the sphere model would predict a comparable amplitude. The rocket had a peak signal of 7000 mV for the vertical orientation. The amplitudes plotted in Figure 20 are relative to this peak amplitude. The vertical orientation has a signal that is narrower than the sphere model and larger in amplitude. The along-track orientation has a signal that is different in shape and amplitude. The cross track orientation has a signal similar in width to the sphere model. We are currently investigating these observed EM signatures and will discuss their exploitation in a later report.

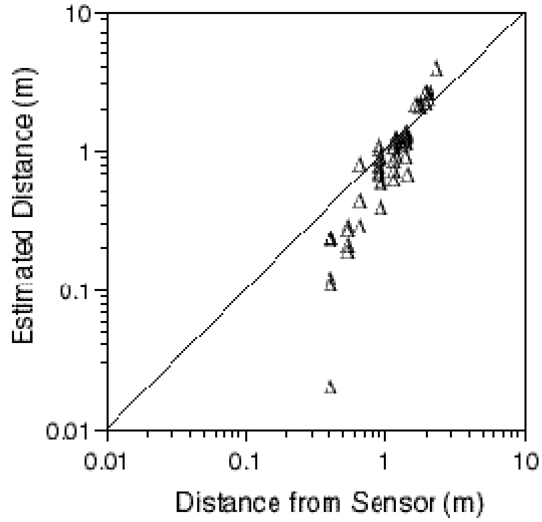

Figure 18. DAS estimate of the distance below the EM sensors vs the actual ordnance distance

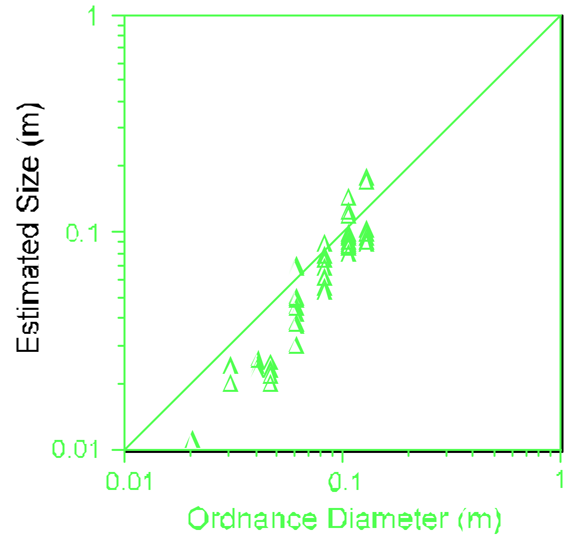

Figure 19. DAS estimate of ordnance size from measured EM signatures vs actual ordnance diameter

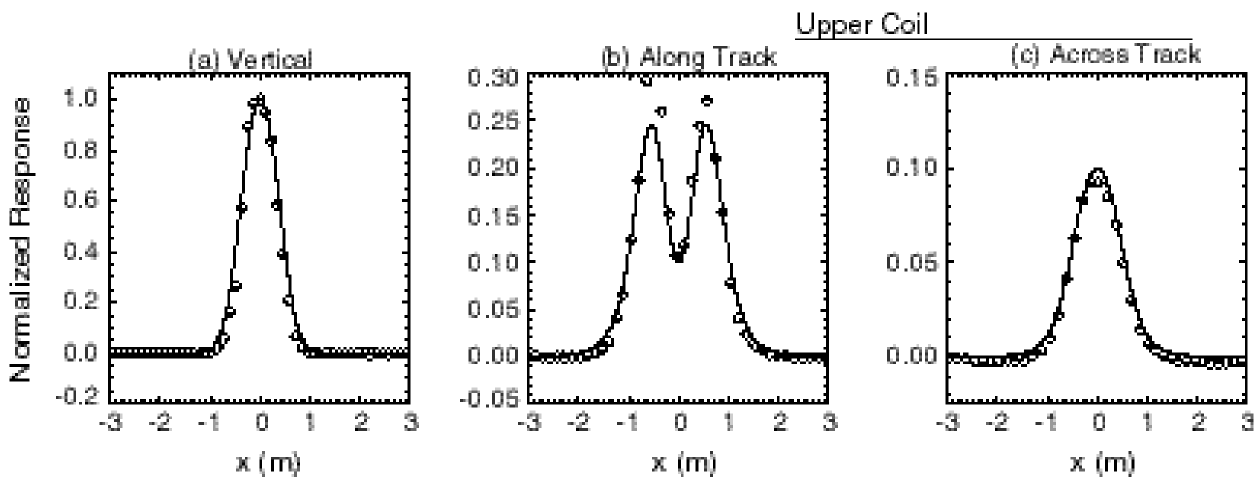

Figure 20. Measured EM signatures of a 2.75" rocket 0.25 m deep oriented (a) vertically, (b) horizontal along the direction of travel of the survey vehicle, and (c) horizontal perpendicular to the direction of the survey vehicle

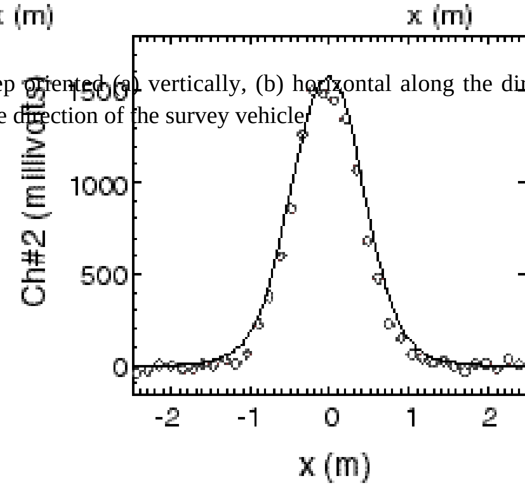

Figure 17. Measured EM signature of a 16 lb ferrous sphere at 0.25 m

REFERENCES

1. "Handheld Gradiometer Survey Test at The Marine Corps Air Ground Combat Center, Twentynine Palms, CA," NAVEODTECHCEN TR, September 1992. This report describes hand-held magnetometry surveys of the MCAGCC Magnetic Test Range conducted by military EOD teams. The ordnance detection efficiency of the EOD teams at this site varied between 25% and 35%.

2. "ESTCP *MTADS* Program Management Plan," J.R. McDonald and Richard Robertson, MTADS/6110-9511/Revision 9, 8 July 1996.

3. "Magnetic Sensor Field Tests and Evaluations for Towed-Array Systems, Ft. Devens, MA," J.R. McDonald and Richard Robertson, NRL/PU/6110--96-303, 2 April 1996.

4. "Multi-sensor Towed Array Detection System (*MTADS*). An Automated High-Efficiency Survey System for Characterization of Ordnance and Explosive Waste (OEW) Sites," J.R. McDonald and Richard Robertson, Proceedings of the UXO FORUM 1996, Williamsburg, VA, 26-28 March 1996, p. 53.

5. "Performance of Electromagnetic Induction Sensors for Detecting and Characterizing UXO," Bruce Barrow, Nagi Khadr, and H.H. Nelson, Proceedings of the UXO FORUM 1996, Williamsburg, VA, 26-28 March 1996, p. 308.

6. "Magnetic Sensor Field Tests and Evaluations for Towed Array Systems, Ft. Devens, MA," J.R. McDonald and Richard Robertson, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, The Environmental and Engineering Geophysical Society, Keystone, CO, 28 April - 2 May 1996, p. 451.

7. "The Combined Use of Magnetic and Electromagnetic Sensors for Detection and Characterization of UXO," Bruce Barrow, Nagi Khadr, Robert DiMarco, and Herbert H. Nelson, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, The Environmental and Engineering Geophysical Society, Keystone, CO, 28 April - 2 May 1996, p. 469.

8. "Operator's Manual for the *MTADS* Tow Vehicle," Chenowth Racing Products, Inc., El Cajon, CA.

9. "Shop Maintenance, Service, and Repair Manual for the *MTADS* Tow Vehicle," Chenowth Racing Products, Inc., El Cajon, CA.

10. "Repair Parts Manual for the *MTADS* Tow Vehicle," Chenowth Racing Products, Inc., El Cajon, CA.

11. "Unexploded Ordnance Advanced Technology Demonstration Program at Jefferson Proving Ground (Phase I)," U.S. Army Environmental Center, Report No SFIM-AEC-ET-CR-94120, December 1994.

12. "Evaluation of Individual Demonstrator Performance at the Unexploded Ordnance Advanced Technology Demonstration Program at Jefferson Proving Ground (Phase I)," U.S. Army Environmental Center, Report No. SFIM-AEC-ET-CR-95033, March 1995.

13. "Unexploded Ordnance Advanced Technology Demonstration Program at Jefferson Proving Ground (Phase II)," U.S. Army Environmental Center, Report No. SFIM-AEC-ET-CR-96170.

14. "Multi-sensor Ordnance Signatures for Algorithm Development and Model Training" H.H. Nelson, J.R. McDonald and R. Robertson, Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, Reno, NV, 24 - 27 March 1997, p. 863.

15 "Processing and Analysis of UXO Signatures Measured with *MTADS*," B. Barrow, R. DiMarco, N. Khadr, and H.H. Nelson, Proceedings of the UXO Forum 1997, Nashville, TN, 28-30 May 1997, p. 8.

16. "Collection and Analysis of Multi-Sensor Ordnance Signatures with *MTADS*," Bruce Barrow and H.H. Nelson, *Journal of Environmental and Engineering Geophysics*, submitted.

17. "Microwave and Differential GPS Navigation Systems; Field Performance Tests," J.R. McDonald, H. H. Nelson, and Richard Robertson, NRL/PU/6110--93-244, July 1993.

18. "Shape and Orientation Effects on Magnetic Signature Predictions for Unexploded Ordnance," Tom Altshuler, Proceedings of the UXO FORUM 1996, Williamsburg, VA, 26-28 March 1996, p. 282.